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# DYNAMIC ANALYSIS OF A BUILDING UNDER ROCKET ENGINE PLUME ACOUSTIC LOAD

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Studies have been performed to develop finite-element modeling and simulation techniques to predict the dynamic structural response of Building 4010 to the acoustic load from the plume of high-thrust rocket motors. The building is the Test Control Center and general office space for the E-complex at Stennis Space Center. It is a large single span; light-structured building located approximately 1,000 feet from the E-1 test stand. A three-dimensional shell/beam combined model of the building was built using Pro/Engineer platform and imported into Pro/Mechanica for analysis. An Equivalent Shell technique was developed to simplify the highly complex building structure so that the calculation is more efficient and accurate. A deterministic approach was used for the dynamic analysis. A pre-stressed modal analysis was performed to simulate the weight stiffening of the structure, through which about 200 modes ranging from 0 to 35 Hz were identified. In an initial dynamic frequency analysis, the maximum response over the model was found. Then the complete 3-D distributions of the displacement, as well as the stresses, were calculated through a final frequency analysis. The results were compared to strain gage and accelerometer recordings from rocket engine tests and showed reasonable agreement.

## INTRODUCTION

Building 4010 is a cantilever-arched structure about 1000 feet west of the axis of the E1 testing stand. The building was originally built as a control room and site machine shop. Later, it was extended to accommodate the NASA engineering department at SSC. In 1998, the E1 test stand was re-configured to test high thrust engines. This caused a change to the test environment of Building 4010, which was not considered in its original design. The question regarding the short and long-term effects of the plume acoustic load to the building had to be answered. The purpose of this analysis is to quantitatively determine the dynamic response of Building 4010 under the acoustic load from the plume of the engine, that includes natural frequency, vibration modes, displacements or deflections, velocity, acceleration, and stresses everywhere in the structure.

Dynamic response of buildings under acoustic waves emitted from rocket engine plume has attracted more and more attention in recent years. Elishakoff et al.[9] studied the dynamic response of a launch site weather protection system using an extended Timoshenko beam theory. Yang[21] simulated the plume acoustic response of a concrete slab structure at Kennedy Space Center using a commercial FEA code. Balakrisina Rao[2] did an analysis on the same structure based on actual measurements. Caimi and Margasahayam[3] studied the response of a test strip placed on the launch pad and suggested a prediction method based on the equivalent load concept.

The analysis of structure dynamics can be divided into two broad categories. In the first category, dynamic response relations of typical or special geometry or material properties are found, which can be solved by numerical or closed form solution. The second category is based on so called ¡ numerical experimentation¡¬. Commercial or proprietary codes are applied to structures with general configurations. Though the methods in the first category lead to fundamental new understandings of the physical phenomenon, they are not easy to apply to practical engineering applications, which are generally more



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complicated and less typical. For the second category, the common difficulty is that even with today¡¦s computing power only very simple problems can be solved. For more complicated problems, the analysts may have to choose between limiting the scope to problems simple enough to solve and using extremely coarse computation grids to include more structure features. As it known to all, coarse grid inevitably compromises numerical convergency as well as physical accuracy. Engineering world has been looking for methods to solve real-life structure dynamic problems. To meet this need the Equivalent Shell method is proposed in this research.

The concept of the Equivalent Shell is straight-forward: Material properties are generally tested by physical experiments. When a piece of specimen is tested, its microscopic features are ignored. Instead, only its macroscopic features are tested and measured. The same approach can be applied to all kinds of structures. A big structure, such as a building or aircraft fuselage, consists of millions of small pieces of structural elements. In most cases, the dynamic behavior of the individual elements is not the concern, or the correlation between individual structure element and the complete building is small. Thus, in a dynamic analysis small structural details may be ignored but the overall effects of the structure features can be tested. This test can be performed on a piece of physically as-built structure. However, it will be much more economical and practical to analyze numerical models, particularly shell models.

In the early days of computer technology, dynamic structure analysis was mainly modeled by beam elements. The reasons were, first, the available computer hardware capability; second, the type of building first attracted the attention of new dynamic tools was high-rise skyscrapers. This type of building is loaded on it steel frame only. For quite some period of time this formed a perfect match between the needs and the availability. However, due to the quick evaluation of computer capability, researchers started to' extend their scope to more complex structures. Mathematically, shell adds one more dimension to beam models. Physically, shell is the most extensively used structure form in aerospace and civil engineering due to its high cross section constant to weight ratio. Any structure, if one of the overall external dimensions is an order, or orders, of magnitude smaller than the other two, the structure can be modeled as an Equivalent Shell.
The basic steps to build an Equivalent Shell are: Two computer models are built, one is the real physical configuration of the complex structure, the other is a single piece of shell with anisotropic material properties. Apply external loads or displacement to the boundary of the complex structure model, find out the boundary resultant forces and moments through analyses. Repeat the same numerical test to the anisotropic shell model. Adjust the corresponding anisotropic stiffness coefficients until the resultant forces and moments are the same as that of the complex structure model. The Equivalent Shell properties are thus determined. When the shell is applied as part of a large structure, the model size is a small fraction as that of the ¡ realistic¡-model while macroscopically they behave the same.

## THE MODEL

The building has eight sections. Seven main beams and two end-wall beams arched through the transverse span of the building and take all the structural loads. The main beams are fabricated I-beams. The web is tapered and the flange thickness changes to optimize the loading condition. The end-wall beams are much smaller since they are supported by wall posts. The section is defined as the distance between two main beams. Eleven pairs of girts, ¡ Z¡- shaped steel beams, bridge across the section to connect the two next main beams. Corrugated aluminum panels are riveted on the top of the girt and cover up all the outside surface. To put a complex structure as Building 4010 into a computer model, some simplification is needed. The requirements for the model are:

1. It has to correctly incorporate all the major physical properties of the building such as flexibility, mass distribution, etc.
2. The model has to be simple enough to be solvable by today¡¦s computer.

In other words, the model has to be simple enough to match the computer hardware and software capabilities and complex enough to give realistic results.

A finite element analysis code Pro/Mechanica was used to build the model. Several attempts were made to find a common ground for these requirements. The first model was an all-beam model. All the main beams, posts, and girts were modeled as beam elements. All the roof and wall panels were omitted. Model #1 showed some unrealistic dynamic behavior. For example, the complete building had a high response to a very low frequency side to side oscillation, which is physically unrealistic and wasn¡¦t observed in testing data. Also, the tapered

main beam could not be properly modeled due to software limitation.

The second attempt, model #2, was an all-shell model. A component of it is shown in Figure 1. Compared to Model # 1 this model realistically simulated wall/roof panel and the tapered main beam. However, it was found that it needed huge number of elements which beyond the capability of the computer. That¡ﬁ because the main beam flanges are long narrow strips. Numerically element aspect ratio needs to be controlled within certain range to keep calculation error small. To meet the aspect ratio requirement, a narrow strip needs to be broken down into smaller elements. This process expends the element number.

The third model was a shell/beam combined model. All the panels are modeled as shell elements, girts and posts use beam elements. A way of modeling the tapered main beam was found: the webs in shell and flanges in beam element. The element grid can be very coarse and the element number is small. The problem with Model #3 is that it would not converge. The problem was investigated and explained: The 22 girts bridged across the space between the two main beams are modeled as beam elements. Between them are the corrugated aluminum panels. Modal analysis used a fitting function to fit the vibration mode from the lowest order polynomial, and increased the order step by step until reached order 9. If the mode was more complex than the 9th order polynomial, the result will start to diverge, which was the case with the panel/girt combination.

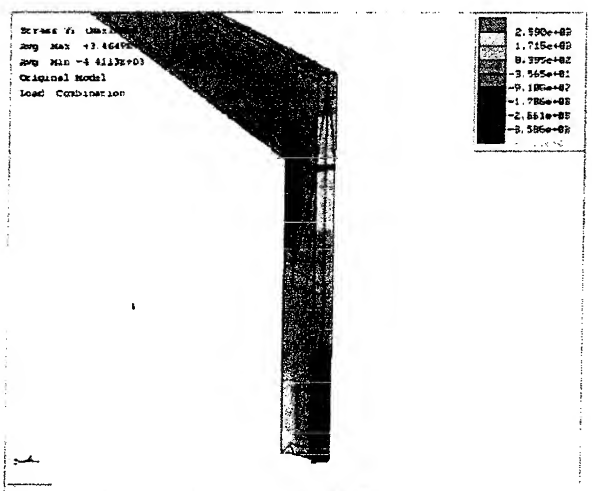

*Figure 1 - Main beam of model #2.*

With the experience of the previous models and the goal of the analysis well defined, a fourth model was created. A new technique called Equivalent Shell was developed which integrated the girts and panels into shell elements with equal total external properties, such as masses and stiffness. With this technique, the model was greatly simplified. What justifies this simplification is that the concern of the problem is the response and integrity of the main structure components under the accumulative load and response of all the panels and girts, not the individual piece of panel. Figure 2 shows Model #4. The grids in the picture are shell elements. Figures 4 shows the model vibrating at different modes. Model # 4 is the final model for this analysis. It has about 400 beam elements and 450 shell elements of ¡ P¡ – type.

As it is described, the roof and wall of Building 4010 is a layer of cold-rolled corrugated aluminum sheet metal panel riveted on the girts. This structure covers up the outside surface of the entire building and plays a critical role in its dynamic behavior. First, it receives the acoustic energy and transmits it to the beam structure. Second, it provides some rigidity to the building, which determines the vibration response. The mechanical stiffness of this combination is quite different from one direction to the other. If a shell model is used to simulate this combination, isotropic shell property is no longer an acceptable assumption. Instead, the anisotropic shell properties must be included.

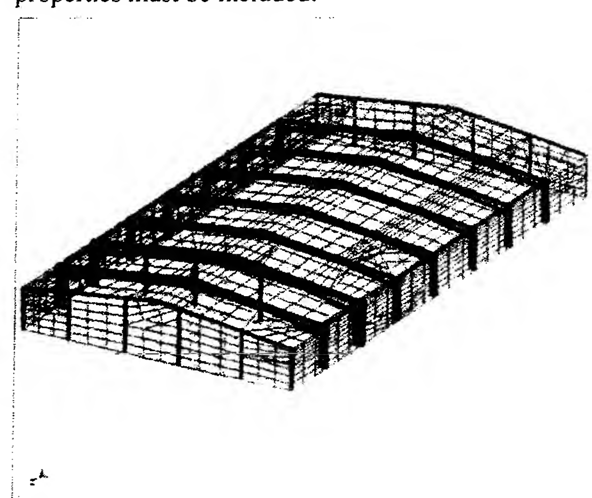

*Figure 2 - Beam/shell combined P element model, #4.*

To determine the property matrix of the roof and wall, two models were built. One is a piece of flat shell and the other is a section of typical panel structure (Figure 3). The shell property is determined by specifying the same displacement of the two models. The property matrixes are adjusted until the resultant forces at the boundaries of both models are the same. Each element in the matrixes is determined by one test case. There are total of 21 elements in the extensional stiffness matrix A, extensional-bending

coupling matrix B, bending stiffness D and transverse stiffness matrix T (Table 1). The actual testing number can be substantially reduced by using corresponding relations and simplified assumptions. For this particular case it is assumed that there exists a mid-plan to which the roof is symmetric, which leads to all-zero elements in the B matrix. A11 and A22 are determined by normal tensile test in X and Y direction. Based on which A12 is calculated. A66 is tested out X-Y shearing case. Since the roof structure is orthotropical, A16 and A26 equal to zero. Either D11 or D22 is determined by bending testing case. Using proportionality between extensional and bending stiffness, all the other elements in D matrix are determined. A55 and A66 are tested out by X-Z and Y-Z shearing cases. Assuming X-Z shearing is independent from Y-Z shearing, A45 equals to zero. The resulting matrices are listed in Table 1.

*Table 1 - Bldg. 4010 Wall/Roof Panel Stiffness Coefficients.*

| | | | | | |
|---|---|---|---|---|---|
| Extensional Stiffness | | | | | |
| A11 | 346.975 | A12 | 104.092 | A16 | 0 |
| | | A22 | 710.001 | A26 | 0 |
| | | | | A66 | 152.026 |
| Extensional-Bending Coupling | | | | | |
| B11 | 0 | B12 | 0 | B16 | 0 |
| | | B22 | 0 | B26 | 0 |
| | | | | B66 | 0 |
| Bending Stiffness | | | | | |
| D11 | 3.90E+06 | D12 | 1.17E+06 | D16 | 0 |
| | | D22 | 8.15E+06 | D26 | 0 |
| | | | | D66 | 1.75E+06 |
| Transverse Stiffness | | | | | |
| A55 | 216.929 | A45 | 0 | | |
| | | A44 | 103.755 | | |

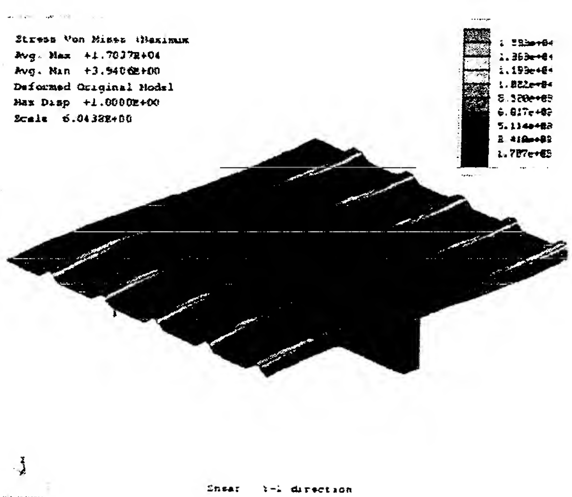


*Figure 3 - Equivalent-shell X direction bending case.*

The deterministic approach is used to simulate the rocket plume acoustic load The sound pressure generated by a rocket plume is a random loading. However, it can be assumed that in a given period of time the acoustic wave has a statistically determined character, i.e. the signal spectrum is stabilized. Under that assumption the deterministic model to solve a random loading problem. This approach was used in the analysis. The sound pressure power spectrum density (PSD) is based on a microphone recording of an engine test.

The main structures of the building are subject to both static and dynamic loads. The static load is the dead weight of its own, which does play a role in the dynamic analysis. Because of the dead load, the building is stiffened and its natural frequency will move upward. This load is calculated in a static analysis and all the other later analyses are based on its results.

The dynamic load is the acoustic pressure generated by the rocket plume. For validation purposes, this load was taken from the microphone recording of a recent engine test. The acoustic load is assumed evenly distributed on the outside surface of building. It is understood that the real acoustic field would be more complicated. The sound waves could reflect, distort, absorbed, cancel or enhance each other in different locations in the space. Detailed description should be accomplished by a numerical acoustic analysis which was beyond the scope of this analysis.

In Building 4010, all main beam and end-wall posts are held down to the concrete foundation by four anchors. Correspondingly in the model all six Degrees of Freedom (DOF), translation and rotation in X, Y, Z directions, were specified fixed at the root. The physical interpretation of this constraint is that the beams are cast into the concrete. Later calculations show that for the given stiffness of the complete building, the bending moments on the beams are very small, which makes this assumption very close to the reality.

Structure damping is caused by the friction between the molecules or between components, or by the agitation of the air around the structure. The damped energy is dissipated in the air in the form of heat. For a linear analysis, damping is assumed to be proportional to the vibration velocity. The damping coefficient or damping ratio used in the analysis is defined by its ratio to the critical damping, which is defined by the damping intensity at which oscillation dies out before it passes the neutral point. A 2% damping coefficient is used for all components, which is commonly used for steel structures.

The bracing-bars are the round shaped steel rods used to stabilize the structure Their role in building

dynamic properties is investigated, and a testing case was run. A bracing bar was added on to a piece of anisotropic shell. It was found that the bracing increased no more than 5% of the stiffness. In the final model they were omitted.

## SOLUTION PROCEDURE

After building the model, assigning material properties, specifying constraint and load, the model is ready to be solved. The procedures for the current case are as follow:

1. Static analysis
2. Pre-stressed modal analysis
3. Initial frequency analysis
4. Final frequency analysis

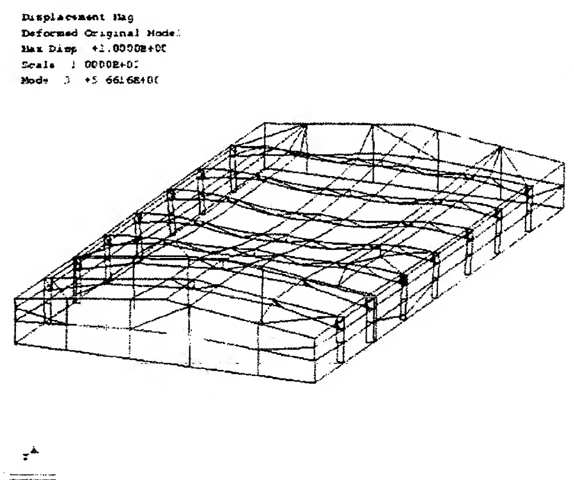


*Figure 4 - Mode #3, 5.6615 Hz (displacement exaggerated).*

The static analysis required the weight-stiffening information for the structure. Based on which modal analysis is performed, each of the modes represents a vibration mode. For example, Figure 4 is mode 3 at 5.6616 Hz. The modes are properties of a given structure and are independent from the load.

Dynamic Frequency analyses are done in two steps. The difference between the initial and final frequency analysis is that initial frequency analysis provides the response curve as a function of frequency. The curves could be any selected physical quantity such as acceleration, displacement or stress. They can be either on the selected locations or set to be the maximum over the model. Initial result tells at which frequency the building responds the most The final frequency analysis provides the complete distribution of stress, displacement, and other quantities over the building. These outputs give a complete description of the motion and loading condition of the building at selected frequency.

## THE VIBRATION TEST

In order to validate the analysis procedure and results, an extensive program was undertaken to measure the response of Building 4010 during actual rocket engine testing. Vibration, strain, and acoustic load data were obtained throughout testing of the rocket engine at the E-1 facility to provide experimental inputs for comparisons with predicted values. Microphones were located at various points to measure the acoustic load on the building during engine firings. Accelerometers and strain gages were mounted at selected points on the main structure beams. These locations were chosen based on the initial analysis which revealed where high stress was likely to occur. A summary of the instrumentation employed and data acquisition methodology utilized is given below.

A total of thirteen (13) strain gages were monitored during the tests. Both single axis type CEA-06-500UW-120 and rosette type CEA-06-250UR-120 gages were used. The gages were installed in quarter-bridge configuration using three-wire termination with bridge excitation and all other signal conditioning supplied by Dynamics, Inc. Model 7600A signal conditional amplifiers. Calibration was by standard precision bridge shunt techniques. Output of the signal condition amplifiers was digitized by a RACAL Storeplex Delta signal processing unit (SPU). Sample rate for the SPU was 25,000 samples per second for each data channel. Serial output from the RACAL SPU was transferred via fiber optic link to a RACAL Storeplex Delta recorder located in the test control center.

Three strain gage measurements are needed just to describe the two-dimensional stress at one point. Since the total number of data channels was limited, only one strain gage measurement was recorded at each point. This allowed more locations to be measured. This one channel was aligned with the primary direction of strain. The test result was then compared with the strain result of the analysis, while the stress condition at the point was obtained by analysis only.

A total of thirteen (13) channels of accelerometer data were obtained during the test series. The Endevco Isotron piezoelectric accelerometer units were bolted to aluminum blocks that were then attached to the building structural members using high strength epoxy. Accelerometer signal condition

was provided by an ICP, Inc. Model 584 signal conditioning amplifier. As with the strain gage signals, accelerometer data was digitized and recorded using the RACAL Storeplex SCU and recorder system described above.

The strain gage and accelerometer signals were recorded at a sample rate of 25,000 samples per second. Due to the distance between the test stand and the building, acoustic signals reach the building about one second later than time zero, the engine ignition time. Data recording started approximately three seconds prior to engine start and terminated approximately two seconds after engine shutdown. This time window is large enough to ensure that no data is lost. It shows that steady state vibration is reached only after about one second. Considering that we are modeling a steady state vibration, the later four- second signal is used for comparison and transformed into frequency domain through an FFT process

Sound pressure levels were obtained at three locations. Data from one location, at the exterior east side of Building 4010, provided the primary data for building vibration analysis. The other two locations, inside the high bay and test control room, were chosen to provide characterization and documentation of personnel exposure levels during testing. The acoustic transducers used for all measurements were Bruel & Kjaer Falcon Model 4191 microphone elements with B&K Model 2669 integral preamplifiers. Signal conditioning of the preamplifier outputs was accomplished using a NEXUS signal conditional amplifier. Data was recorded on a TEAC Model XR-7000 20-channel cassette data recorder operating with a tape speed of 76 centimeters per second. The data was digitized post test at a sample rate of 84,000 samples per second.

## RESULT AND DISCUSSION

The first step is a static load analysis to provide information of static load stiffing. The result is shown in Figure 7. The maximum sagging at the center of the roof is .36 inch and maximum stress (not shown) is about 7 ksi. A Pre-stressed Modal Analysis was done on the statically loaded model. About 200 modes were obtained ranging from 0 to 35 Hz. For each one of the modes, a three-dimensional model displacement result can be show. Figure 8 is the vibration of the building in mode 3, 5.6616 Hz. Figure 4 is the alternative display of the same mode with the motion of the roof exaggerated. The white line across the roof and the wall is the gap between the old and new section with internal posts located. Because of that the vibration of the roof at this mode is confined to the old section of the building. Figure 9 is the vibration of mode 45, 11.228 Hz. The vibration is mainly in the extended section, especially the end-wall. Figure 10 is the vibration at mode 190, 30.338 Hz, with one of the major stress peaks located as shown in Figure 6. The high stress spot is at bottom of the center joint of the main beam. The maximum Von Mises stress is 35 ksi.

The initial frequency analysis is done at pre-selected points, at which the measuring quantities such as displacement, acceleration or stresses are specified. The results of the initial frequency analysis are response-frequency curves. The left two pictures in Figure 5 are examples of such results. The purpose of this group of output is to validate the analysis. Their location and measuring quantities are chosen according to the strain gage and accelerometer positions and directions. The right top picture of Figure 5 is the actual strain gage reading. The comparison shows that the major characteristic of the vibration is correctly captured. The measured peak is slightly lower than the modeled. That is because the real main beam is flange-bolt connected, which and is slightly less stiff than the modeled which are equivalent to weld joints. The problem can be corrected by adding a component modeling to modify the properties of the main beam. The right-bottom picture is the actual accelerometer recording. The peaks are more scattered in the recorded than the modeled. The explanation for this difference is that there are numerous small items such as lights, cables and other devices are attached to the main beams and girt. These attachments changed the natural frequency of the structure component and created more peaks in the spectra.

The maximum response all over the model can also be obtained as shown in Figure 6. It is interesting to find out the highest response didn¡ft happen at the lowest frequency as it is always the case in single degree of freedom (SDOF) problems. The difference between Figure 5 and 6 is that the former is ¡-measured¡- at specific point but the later scanned the highest response all over the model and output the maximum disregarding the position. This is a very useful output since from safety point of view what concern us are the highest stress values and their positions. Figure 6 shows there are three major and one minor stress peaks. Each of these peak frequencies can be selected to perform a final frequency analysis. The result is a space distribution of the stress. Figure 11 is an example of the stress distribution at 5.6616 Hz, the minor peak in Figure 6

From the stress distribution picture the high stress or problem spot can be identified and assessed.

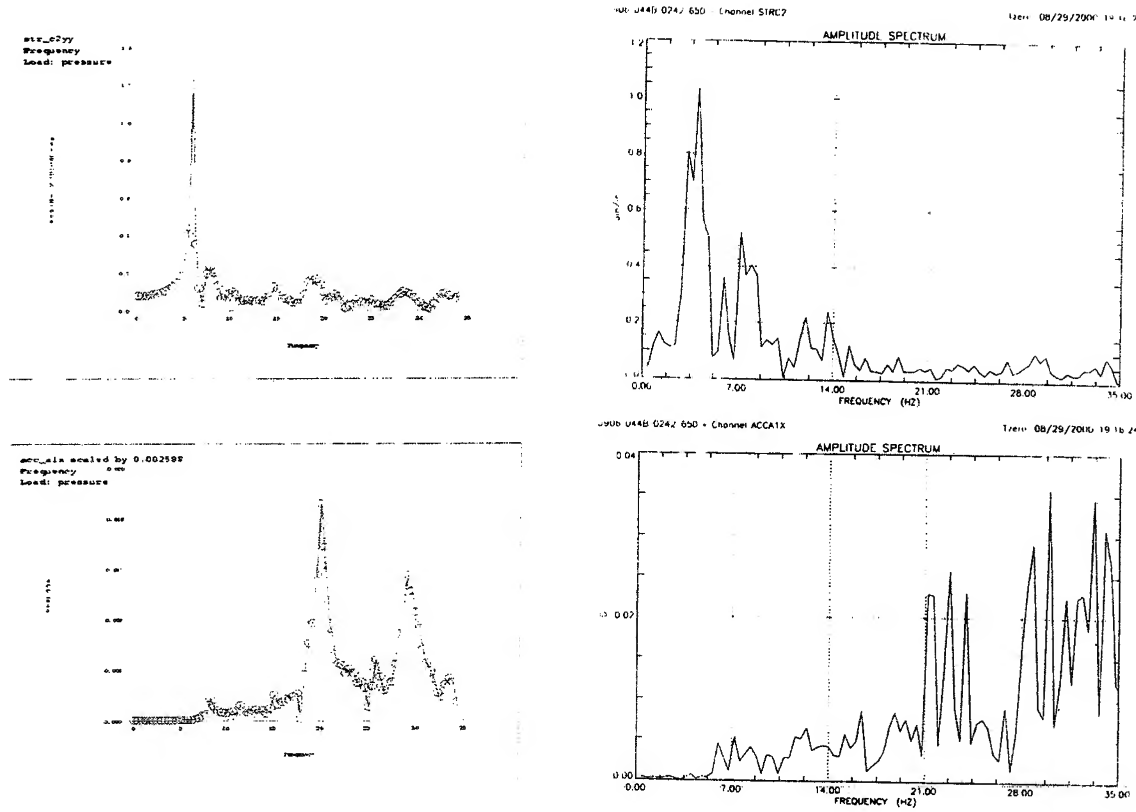


*Figure 5 - Top left: Modeled strain. Top right: Measured strain at the same point. Bottom left: Modeled acceleration. Bottom right: Measured acceleration.*

Table 2 is a list of the peak frequency of displacement in X, Y and Z direction and the peak stresses. From which it is found that there is no correlation between peak stress and peak displacement in all frequencies except at mode 3 and mode 49.

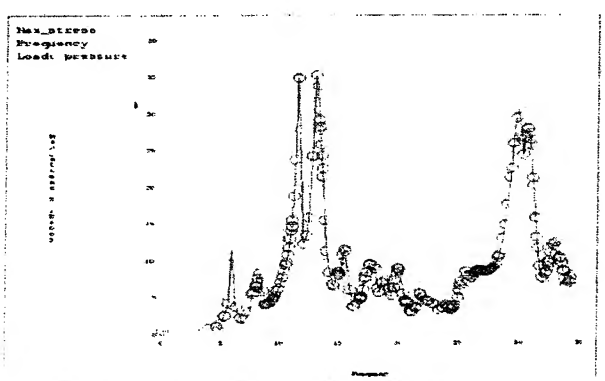


*Figure 6 - Peak stress over all modes.*

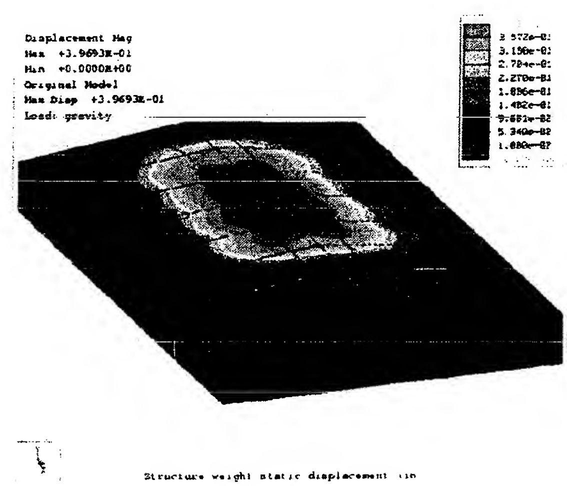


*Figure 7 - Static load displacement.*

*Table 2 - Peak Stress/Displacement Response Modes*

| Mode # | Hz | Disp. X | Disp. Y | Disp. Z | Stress |
|---|---|---|---|---|---|
| 3 | 5.6616 | | * | | * |
| 16 | 8.0768 | | | | * |
| 44 | 11.123 | | | | * |
| 45 | 11.227 | | * | * | |
| 49 | 12.65 | * | * | | * |
| 50 | 12.8 | | | * | |
| 70 | 15.13 | | * | | |
| 182 | 29.15 | * | | | |
| 184 | 29.51 | | | | * |
| 190 | 30.33 | | | | * |

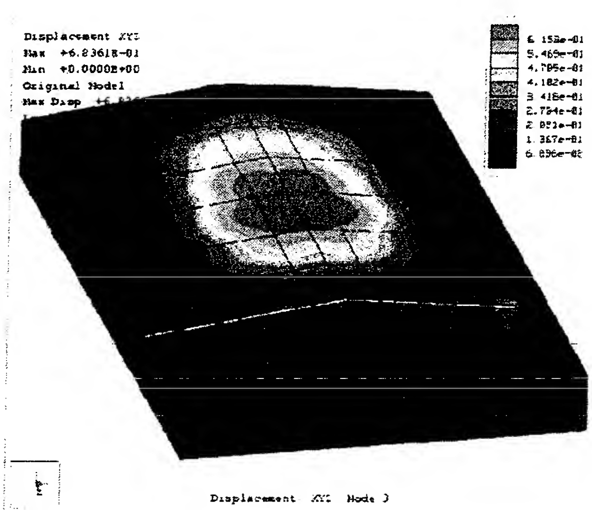

*Figure 8 - Displacement, Mode 3.*

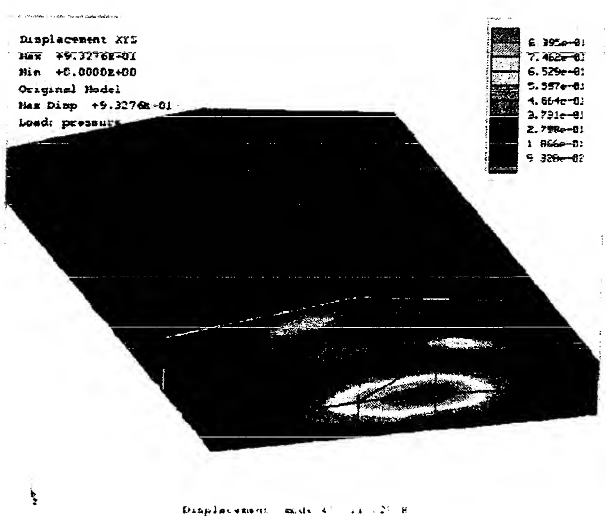

*Figure 9 - Displacement, mode 45, 11.228 Hz*

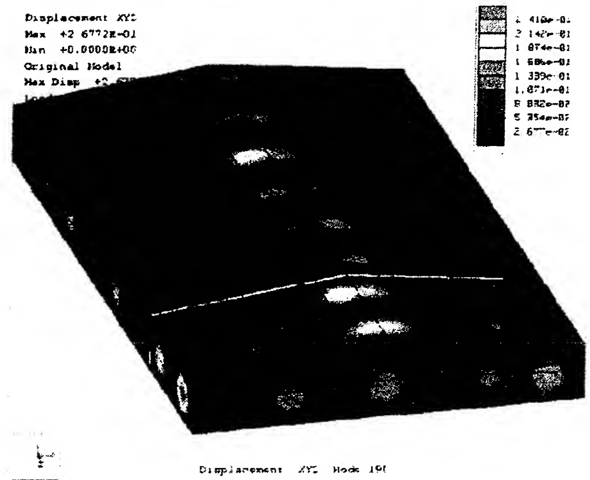

*Figure 10 - Displacement, Mode 190.*

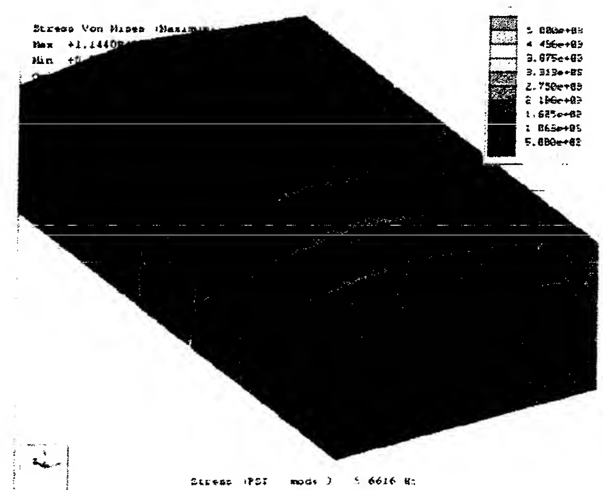

*Figure 11 - Stress, Mode 3.*

## CONCLUSION

A method to analyze dynamic response of a building under the rocket engine plume acoustic load is presented. The Equivalent Shell method significantly simplified the model, which made the simulation possible. The technique can also find its application extensively in a variety of static and dynamic problems.

The anisotropic properties of the Equivalent Shell were successfully obtained by the model test method. The beam-shell combined model was used to simulate the complex and critical main beams which are more

efficient and accurate than other modeling methods. Pre-stressed frequency analysis was performed to take the static-stiffening into consideration. Three-dimensional distributions of stress, displacement and acceleration were obtained at every mode. The analysis found that, contrary to most SDOF analysis results, the peak dynamic response might not happen at the lowest frequency mode. It is also determined that for the building in dynamic environment the static stress could be a small fraction of the total stress. Microphone, strain gage, and acceleration measurements were performed in engine fire tests. The analysis result agrees with the measurement on major physical characteristics.

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**13. ABSTRACT *(Maximum 200 words)***

Studies have been performed to develop finite-element modeling and simulation techniques to predict the dynamic structural response of Building 4010 to the acoustic load from the plume of high-thrust rocket motors. The building is the Test Control Center and general office space for the E-complex at Stennis Space Center. It is a large single span; light-structured building located approximately 1,000 feet from the E-1 test stand. A three-dimensional shell/beam combined model of the building was built using Pro/Engineer platform and imported into Pro/Mechanica for analysis. An Equivalent Shell technique was developed to simplify the highly complex building structure so that the calculation is more efficient and accurate. A deterministic approach was used for the dynamic analysis. A pre-stressed modal analysis was performed to simulate the weight stiffening of the structure, through which about 200 modes ranging from 0 to 35 Hz were identified. In an initial dynamic frequency analysis, the maximum response over the model was found. Then the complete 3-D distributions of the displacement, as well as the stresses, were calculated through a final frequency analysis. The results were compared to strain gage and accelerometer recordings from rocket engine tests and showed reasonable agreement.

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Building, structural dynamics, acoustic loads, vibration/strain analysis

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